

## **Transport, Fate, and Effects of Sludge Disposal at the 106-Mile Site: A Summary and Synthesis of Findings**

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### **ABSTRACT**

The Ocean Dumping Ban Act of 1988 resulted in the implementation of a major research and monitoring program designed to evaluate the fate and effects of sewage sludge dumped at the 106-Mile Deepwater Municipal Sewage Sludge Dump Site. This multi-year program used an array of traditional and state-of-the-art techniques, both in the field and in laboratories, to evaluate the physical and chemical fate of 42 million wet tons of sewage sludge dumped at the 106-Mile Site, and to determine whether the disposal caused biological impact. These studies were augmented by numerical, probabilistic, and circulation models that evaluated the interaction between the sludge, local ocean currents, general circulation in the northwest Atlantic Ocean, and the continental shelf.

The field and modeling studies demonstrated that the sewage sludge dumped at the 106-Mile Site was transported along two primary pathways after disposal. Larger, rapidly settling particles, were transported through the water column and deposited in sediments on the continental rise within and immediately to the west of the 106-Mile Site. Particles that settled at rates less than 0.04 m/s were transported in the water column towards the southwest until the water and particles interacted with the Gulf Stream. Following this interaction these particles were rapidly transported into the northwest Atlantic Ocean. Both numerical and circulation models estimated that the sludge particles that reached the sediments were confined to a narrow band extending about 100 km to the southwest of the 106-Mile Site. Elevated levels of chemicals and other sludge tracers were measured in sediments from this predicted area of deposition. In the sediments, the concentration of chemical tracers of the sludge decreased towards the southwest as distance from the Site increased and were generally not observed above background levels at distances greater than 50 km from the Site. Spores of the enteric bacteria *Clostridium perfringens* in sediment samples were measured above background levels up to 100 km southwest of the Site. The spatial extent and decreasing gradient with distance from the Site of this sludge tracer were consistent with the depositional footprint developed by the transport and fate models. Data

from an array of deep-sea sediment traps also confirmed the transport of sludge to the sediments of the continental rise. The sludge-related flux of contaminants through the water column decreased with increasing distance from the Site and were detected above background at distances up to 100 Km to the southwest of the 106-Mile Site. In addition, oxygen consumption rates increased in the sediments to the southwest of the 106-Mile Site, suggesting that the organic matter was enriched in these sediments resulting in elevated oxygen consumption rates. Depending on the sludge settling rates used, the models estimated that between 25 and 70 percent of the sludge dumped at the Site was deposited in this narrow band of sediments. Mass balance estimates using chemical tracers of the sludge suggested that at least 30 percent of the sludge reached the seafloor. This estimate is imperfect since loss of the chemical tracers during settling through the water column, differential transport in association with particles of different sizes, or post-depositional degradation of some tracers appears to have occurred. Notably, oxygen consumption rates in sediments near the 106-Mile Site returned to those measured in reference areas within one year of the cessation of sludge disposal, suggesting a rapid loss of sludge derived organic matter from these sediments.

Evidence of sludge transport to the submarine canyons located on the outer continental slope or to the continental shelf was not found. Probabilistic models based on data collected during the study indicated that likelihood of transport to the shelf was extremely low ( $<0.0001$ ). Satellite tracked surface drifters and sea surface temperature images directly confirmed that the surface waters passing through the 106-Mile Site did not move onto the continental shelf and that approximately 20 percent of the drifters recirculated through the 106-Mile Site. Movement of sludge onto the continental slope and shelf was not evident in the sediment trap results nor from the studies conducted in the heads of the submarine canyons of the outer continental shelf.

An extensive measurement program to determine whether chemical contaminants associated with the sewage sludge could be detected in fish and shellfish did not find significant evidence of bioaccumulation in commercially valuable species of lobster, red crab, and tile fish collected from the continental shelf and canyons, in deep-sea finfish and shellfish collected from the continental rise and slope, or midwater fish collected from the vicinity of the 106-Mile Site. Extensive sampling of lobster and red crab from throughout the continental shelf of the northeast coast of the United States found chitinoclasia shell disease to be ubiquitous in these organisms. However, causative linkage to sludge dumping at the 106-Mile Site was not found. Sludge-related impact was not detected on the deep-sea fish community of the continental rise nor the benthic communities from the heads of submarine canyons of the continental slope. Degradation of the deep-sea benthic community in the vicinity of the Site was not reported, although data from 1989 suggested sludge disposal may have enabled benthic species that are more representative of the continental shelf than the continental rise to inhabit the sediments near the 106-Mile Site. This response was likely due to the increased input of organic matter to the sediments from the dumping. Reduced sewage sludge dumping rates required after August, 1989 likely reduced the flux of sludge to sediments of this region. This reduction in dumping rates may have contributed to limited impact detected during the last two years of disposal.

## INTRODUCTION

The 106-Mile Deepwater Municipal Sewage Sludge Dump Site (106-Mile Site) was designated to receive sewage sludge in 1984. Disposal operations at the Site began in 1986 and ended, as required by the Ocean Dumping Ban Act of 1988, in 1992. Approximately 42 million wet tons of sewage sludge were dumped at the Site during this period (Hunt *et al.*, 1995a). Monitoring, research, and surveillance of the sewage sludge disposal activities were coordinated through a program developed by the U. S. Environmental Protection Agency, National Oceanic and Atmospheric Administration, and U. S. Coast Guard (EPA, NOAA, USCG, 1989). As evidenced in the preceding series of papers on the 106-Mile Site, papers published in other scientific literature (see for example Redford *et al.*, 1992), and project reports (EPA, 1995), this research and monitoring program was comprehensive and focused on issues relevant to deep-sea waste disposal. This paper integrates the findings of these studies by focusing on the questions posed in the introduction to this series of papers (White *et al.* 1995):

1. Based on sewage sludge characteristics, as well as circulation in the Middle-Atlantic Bight, was it possible to predict where sewage sludge dumped at the 106-Mile Site might be -- or might not be -- transported and deposited?
2. Was it possible actually to find sewage sludge-derived materials at the 106-Mile Site, or elsewhere in the Middle-Atlantic Bight; was it possible to pinpoint dumping at the 106-Mile Site as the source of those materials -- distinct from other activities that introduce sewage sludge to the ocean?
3. Was it possible to detect any bioaccumulation or biological effects of sewage sludge dumped at the 106-Mile Site?

The 106-Mile Site studies provide a comprehensive understanding of the transport, fate, and effects of the sewage sludge dumped at the 106-Mile Site. However, the value of these studies extends beyond the 106-Mile Site program through increased understanding of the fundamental physical, chemical, and biological characteristics of the study region. Had the program not been implemented, these data would not be available to future researchers conducting studies into oceanographic processes of the continental slope and shelf. Perhaps more importantly, the 106-Mile Site program now represents a model for the study and evaluation of oceanic dumpsites in general, and especially those located offshore. Thus, while the studies primarily focused on questions central to the sewage sludge disposal, they also yielded information that has intrinsic value transcending the goals of the monitoring program.

## **SLUDGE TRANSPORT AND FATE - MEASUREMENTS AND PREDICTIONS**

The research and monitoring program employed an array of traditional and state-of-the-art oceanographic tools to measure ocean currents, transport of sludge through the water column, and deposition of sludge in sediments of the continental rise, continental slope and outer continental shelf. The study results clearly demonstrate that sludge dumped at the 106-Mile Site was transported within and through the slope-sea and that a substantial fraction reached ocean sediments in the vicinity of the 106-Mile Site. On the other hand, the study shows just as clearly that sludge dumped at the 106-Mile Site was not transported onto the continental shelf. The major results demonstrating this are summarized below.

*Water transport:* Evidence of the general southwest transport of surface waters in the vicinity of the 106-Mile Site was obtained from plume tracking studies conducted prior to 1989 (Redford *et al.*, 1992; Hunt *et al.*, 1992) by satellite tracked surface drifters (Dragos, *et al.*, 1995; Aikman and Wei, 1995) and sea surface temperature (Berger *et al.*, 1995). Of the 62 drifters released at the 106-Mile Site, all were transported towards the southwest and entered the north wall of the Gulf Stream within a mean time of 27 days. Current meter measurements indicated that the mean southwest drift of the surface water extended to about 500 meters depth and provided additional evidence for the southwest movement of deepwaters on the continental rise (Hamilton *et al.*, 1995). Drifters entrained by the Gulf Stream moved rapidly to the northeast into the northwest Atlantic Ocean. Fifteen percent of the drifters initially moved to the continental shelf break (200 meter depth contour), becoming temporarily associated with the shelf-slope front. However, no drifter crossed onto the continental shelf. Approximately 20% of the drifters recirculated through the slope sea, adding evidence for the large-scale gyre in the slope sea postulated by Csanady and Hamilton (1988). The satellite imagery clearly showed these drifters being ejected from the edge of the Gulf Stream after encountering warm core rings, in association with filaments trailing a meander, or cold domes (Berger *et al.* 1995).

*Sludge transport:* A variety of chemical and other tracers characteristic of the sludge demonstrated that sludge was transported through the water column. Sediment traps deployed in the vicinity of the 106-Mile Site and along the direction of expected transport to the southwest of the Site detected a significant flux of sludge through the water column (Hunt *et al.*, 1995b; Bothner *et al.*, 1994). The highest flux of sludge-related materials was measured within 10 km of the Site, although a flux of sludge related tracers was detected at distances up to 110 km southwest of the Site. The array of deep-sea sediment traps also demonstrated that dispersion of the sludge across the continental rise (north and south direction) was confined to a relatively narrow band to the west of the Site (Hunt *et al.*, 1995b). Sludge transport onto the continental shelf was not evident in the sediment trap results. Rather, the flux data suggested movement of

materials from the continental shelf onto the continental rise and slope, which is consistent with results from previous measurement programs in the region (Biscaye *et al.*, 1988).

*Sludge fate:* Tracers of sewage sludge that were measured in surface sediments collected from the continental rise and slope revealed a distinct pattern of elevated concentrations in and immediately west of the Site. The concentrations in the sediment were highest just west of the 106-Mile Site and decreased towards the southwest. This pattern was most evident for *Clostridium perfringens*, a spore-forming bacterium common to mammals and known to be associated with sewage wastes (White *et al.*, 1992; Hill *et al.*, 1993; Draxler *et al.*, 1995). *Clostridium perfringens* spores were detected in sediments at levels typical of pre-disposal conditions in areas outside of the area of clearly elevated tracers (Draxler *et al.*, 1995).

Chemical analysis of the sediments also revealed a pattern of increased concentrations of certain metals and organic compounds commonly found in sewage sludge (Draxler *et al.*, 1995; Lamoureux *et al.*, 1995; Takada *et al.*, 1994; Bothner *et al.*, 1994). The highest concentrations were confined to a relatively small area within the Site and extending 10-20 km to the southwest of the Site. Metal and organic contaminant concentrations in the sediment outside of this small area were similar to background concentrations and did not display the distinct pattern observed for *Clostridium perfringens* spores (Draxler *et al.*, 1995).

In addition to these tracers, other indicators of sewage sludge demonstrated that the sludge reached the sediments in the vicinity of the 106-Mile Site. These measurements included determination of the stable isotope ratios of carbon, sulfur, and nitrogen (Hunt *et al.*, 1995b; Van Dover *et al.*, 1992) and of sediment oxygen consumption rates (Sayles *et al.*, 1995). The latter increased at least two-fold relative to background levels in the areas receiving the most input of sludge, suggesting elevated concentrations of organic matter in these sediments.

The study program implemented to determine if sludge dumped at the 106-Mile Site had impacted sensitive areas on the outer continental shelf (Cooper *et al.*, 1992) found evidence of anthropogenic contaminants and bacteria in the heads of submarine canyons located in this region. However, correlation of concentration gradients with distance from the 106-Mile Site was not evident (Cooper, 1993). Thus, the anthropogenic signatures in these sediments could not be linked to the disposal activities at the 106-Mile Site (Sawyer *et al.*, 1995).

*Retention of sludge in sediments:* Monitoring of sediments near the 106-Mile Site in 1993, one year after dumping had stopped, revealed a significant decrease in the level of certain sludge tracers. Specifically, the oxygen consumption rates in the sediment receiving the highest input of

sludge had returned to background levels within the year following cessation of disposal activities (Sayles *et al.*, 1995). However, 95 km southwest of the Site oxygen consumption rates remained elevated relative to reference areas. These results strongly suggest that sludge derived organic matter that had reached the sediments was rapidly oxidized (a half-life as low 3 years but no more than 6 years was estimated), although erosion and transport to the southwest of sediments laden with organic matter were postulated to be partially responsible. Such transport is consistent with the current meter results reported by Hamilton *et al.* (1995).

Other evidence for loss of sludge signatures in the sediments was obtained by Lamoureux *et al.* (1995). These authors reported that sediment samples collected near the Site one year after sludge dumping ceased had low concentrations of linear alkyl benzenes (LABs), a class of chemical compounds found to be one of the best tracers of sewage sludge in this environment (Takada *et al.*, 1994; Hunt *et al.*, 1995b,c) although other organic contaminants and silver remained at levels similar to those measured in 1989. The lower LAB concentrations and relatively constant concentrations of other contaminants at these sites in 1993 was surprising, especially considering that about 50 percent of the sewage sludge dumped at the 106-Mile Site occurred after the 1989 sampling. Factors such as sediment erosion and transport to the southwest, as postulated by Sayles *et al.* (1995), were considered by Lamoureux *et al.* (1995) as possible causes. However, more rapid bacterial degradation of the LABs relative to other tracers was postulated by these authors to have been the primary cause. Another factor that may have contributed to these observations is the rate at which barges were allowed to dump sludge. The allowable discharge rate was significantly lowered in August 1989, which increased the amount of initial dilution of sludge at the ocean surface. This may have altered the settling characteristics of the sludge such that a lower fraction reached the seafloor relative to the pre-1989 period. This change in dumping practice, and its impact on settling characteristics of the sludge, was not directly tested during the program.

*Predictive modeling:* Numerical transport (Isaji *et al.*, 1995) and circulation models (Patchen and Herring, 1995) used measurements of the physical oceanographic conditions collected during the monitoring program (Hamilton *et al.*, 1995; Dragos *et al.*, 1995) and settling rates of sludge particles (Lavelle *et al.*, 1988; Albro *et al.*, 1995) to develop predictions of the sludge fate. These models calculated that a significant fraction of the sludge would settle to the seafloor with most of the material depositing within about 60 km of the Site. The depositional patterns or footprint of sludge in the sediment derived from the transport models was similar to that reported by Fry and Butman (1991) and to the *Clostridium perfringens* spore distribution measured in the sediments (White *et al.*, 1993). The more recent models estimated that 25 to 70 percent of the sludge would reach the sediments of the continental rise/slope southwest of the Site. These

estimates were highly dependent on the particle settling rates used in the models (Isaji *et al.*, 1995). Sludge particles that were not deposited were moved to the Gulf Stream and transported out of the region. These models also showed that the sludge would not be transported onto the continental shelf Aikman and Wei, 1995), which is consistent with the probability modeling that showed an extremely small ( $<0.001$ ) potential for transport of sludge particles onto the continental shelf (Churchill and Aikman, 1995).

Uncertainty in the settling rates of the sludge particles was found to be the most limiting factor for developing accurate estimates of the fraction of sludge deposited at the seafloor (Isaji *et al.*, 1995; Paul *et al.*, 1995). For instance, Albro *et al.*'s (1995) estimated settling rates were much higher than those of Lavelle *et al.* (1988). Attempts to validate model estimates using a simple mass balance approach suggested that up to 30% of the sludge dumped at the 106-Mile Site reached the sediments in the vicinity of the Site (Hunt *et al.*, 1995c). Although this result is more consistent with estimates derived using the settling rate regime of Lavelle *et al.* (1988), the comparison is limited because the estimates varied depending on the chemical tracer used to develop the estimate. For example, based on silver about 5 % of the sludge was estimated to reached the seafloor. This compares with about 30 % based on copper and coprostanol. Some of this difference was postulated to result from selective chemical or biological mobilization of the tracers as particles settled through the water column or size specific concentrations of the tracers in the settling particles (Hunt *et al.*, 1995c). The inability to resolve the amount of sludge reaching the sediments accents the need for accurate waste characterization information, including size specific settling rates and tracer concentrations, before more refined estimates of fate can be developed.

## **BIOACCUMULATION**

An extensive suite of contaminant measurements in organisms ranging from deep-sea finfish (Steinhauer *et al.*, 1995; Sennefelder *et al.*, 1995; Gadbois *et al.*, 1995) and shrimp (Sennefelder *et al.*, 1995; Gadbois *et al.*, 1995) to midwater fish (Zdanowicz *et al.*, 1995) to commercially important fish, lobster and red crab (Steimle *et al.*, 1995; Feeley, 1993) were completed between 1989 and late 1991. Contaminant levels in these organisms were not generally elevated and none of the studies were able to link the levels of contaminants to sewage sludge dumped at the 106-Mile Site. Thus, bioaccumulation of contaminants from sewage sludge disposal at the 106-Mile Site could not be identified.

Contaminant concentrations (metals and organic compounds) in the deep-sea finfish and shrimp collected in 1990 and 1991 in the vicinity of the 106-Mile Site (Sennefelder *et al.*, 1995; Gadbois *et al.*, 1995) were low and similar to those measured in similar species in the early and mid 1970s.

Metals and organic contaminants in tilefish, a commercially important finfish harvested from canyons on the outer continental shelf, were also generally low (Steimle *et al.*, 1995). A consistent spatial pattern in contaminant concentrations in the tissues of these organisms was not evident. As in the case of deep-sea organisms, the 1990 and 1991 results were similar to those reported in the early 1980s prior to sludge dumping at the 106-Mile Site (Steimle *et al.*, 1995).

Similarly, an extensive analysis of lobsters and red crabs collected from the heads of submarine canyons of the outer continental shelf did not reveal significantly elevated concentrations that could be related to the sludge dumping at the 106-Mile Site (Cooper, 1993; Feeley, 1993; Baker *et al.*, 1992). Metal and organic contaminant levels were found to be slightly elevated in some canyons relative to others. However, contaminant concentrations could not be related to distance from the 106-Mile Site. Rather, sources such as atmospheric inputs or transport from the inner shelf were thought to be the cause of the differences.

One of the most extensive sets of contaminant measurements on midwater fish was completed under the 106-Mile Site monitoring program. Three years of broad-scale sampling did not identify a consistent increase in contaminant concentrations in fish sampled from the surface waters potentially influenced by the sludge dumping, although elevated concentrations of some metals and organic compounds were sporadically found in an area immediately west of the Site (Zdanowicz *et al.*, 1995). Contaminants accumulating in plankton collected from the surface waters were also sporadically detected, but could not definitively be linked to sludge dumped at the Site (Zdanowicz *et al.*, 1995). Thus, while some short-term increases in contaminant concentrations may have occurred, longer-term bioaccumulation above background levels over a broad spatial scale was not consistently detected in these organisms.

## **BIOLOGICAL EFFECTS**

Studies of biological effects resulting from the sludge dumping included examination of the benthic, microbiological, and deep-sea fish community structure, fisheries landings, and evaluation of the prevalence of chitinoclasia shell disease in lobster and red crab. The benthic and microbial communities in sediments from the continental rise (Straube *et al.*, 1991) as well as communities found at 700 m depth in the submarine canyons of the outer continental shelf (Small *et al.*, 1991; Cooper, 1992) were sampled. These studies did not identify significant impacts that could be related to the sludge disposal, although potential changes to the deep-sea benthic community near the 106-Mile Site were reported (Grassle *et al.*, 1992). The primary biological findings are summarized below.



*Community structure.* Musick *et al.* (1995) reported that the structure of the deep-sea finfish community in the vicinity of the 106-Mile Site in 1990 and 1991 was similar to that described in the early 1970s. Measures of species richness, numerical abundance, depth distributions, and biomass were similar for both sampling periods. Because the structure of this community had not changed relative to pre-dumping, no effects from the sludge dumping at the 106-Mile Site could be identified.

Unlike the deep-sea fish, the bacterial community in near-bottom waters in 1989 had changed from the natural autochthonous bacterial community to a community poorly adapted to the deep-sea conditions (Straube *et al.*, 1991). However, the importance of this change to the ecology of the area was not clearly established. Other indirect measures of bacterial influence on the sediments (i.e., oxygen consumption rates) suggested that the system was healthy. Bacterial and protozoan communities in the submarine canyons clearly included species associated with sewage (Sawyer *et al.*, 1995), suggesting that sewage derived wastes had reached the canyon areas. However, a direct link of these sewage-associated organisms to dumping at the 106-Mile Site was not evident. Rather, the data suggested that offshore transport of sewage-related materials from previous dumping or coastal sources in the New York Bight was the cause.

Analysis of the benthic community near the 106-Mile Site in 1989 suggested that this community had changed compared to results of studies conducted prior to sludge disposal (Grassle *et al.*, 1991). Specifically, polychaete species not previously found in sediments from the continental rise were identified. Because these organisms generally respond to inputs of organic matter, the presence of polychaetes was believed to be related to the deposition of sludge near the 106-Mile Site. The results of follow-up studies conducted in 1991, 1992, and 1993 are not yet available.

In addition to the deep-sea benthic studies, video surveys conducted between 1990 and 1992 at 700-m depth in the submarine canyons of the outer continental shelf determined that the macrobenthic community structure and species abundances were consistent among the canyons (Cooper, 1993). The behavior and habitat associations of the animal populations in the canyons were also consistent and did not appear to be affected by sludge dumping (Cooper *et al.*, 1992).

*Fish abundance.* Species abundances of silver hake (*Merluccius bilinearis*), red hake (*Urophycis chuss*), summer flounder (*Paralichthys dentatus*), goosefish (*Lophius americanus*), and black sea bass (*Centropristis striata*) from trawl surveys of the continental shelf were examined for periods before and during the years of sludge disposal at the 106-Mile Site. During the period of sludge

disposal at the Site, a significant decline in abundances over both temporal and spatial (north to south) scales was found. The reason for reduced abundances of these species was not clear as the data were considered inadequate to determine whether natural causes, fishing pressures, sludge disposal, or combinations of factors were responsible for the observed population fluctuations (Chang, 1993).

*Chitinoclasia shell disease.* Three major studies to determine the prevalence of chitinoclasia shell disease in lobsters and red crabs resident on the continental shelf and canyons in the vicinity of the Site (Ziskowski *et al.*, 1995; Wilk *et al.*, 1995; Feeley, 1993) were completed. These studies, which examined nearly 20,000 organisms from the continental shelf and submarine canyons, determined that chitinoclasia shell disease was common to all populations sampled. The disease was detected in 2-8% of the lobster population; a higher incidence of the disease was associated with lobsters collected from the submarine canyons than with those from the continental shelf (Ziskowski *et al.*, 1995). In female lobsters, the prevalence of chitinoclasia shell disease was significantly higher in areas potentially influenced by sludge disposal at the 106-Mile Site. However, a definitive cause-and-effect relationship could not be established due to probable influence from other sources, notably the former 12-Mile Site which was located in the inner New York Bight.

The incidence of chitinoclasia shell disease in red crabs collected from the canyons and continental shelf was much higher than in the lobster population. Feeley (1993) found that 67-100% of the crab specimens from individual canyons showed some level of the disease. However, no significant trends were found between the incidence of the disease and distance from the 106-Mile Site. Thus, no cause-and-effect linkage with sludge dumping at the 106-Mile Site could be established.

## **DISCUSSION**

Considered as a whole, the information collected under the 106-Mile Site monitoring and research program clearly demonstrated that sewage sludge dumped at the 106-Mile Site could be traced in the ocean. Diverse modeling approaches developed similar predictions of the transport and fate of the sludge within the northeastern Atlantic Ocean. These predictions were confirmed through an extensive sampling and analysis program that used sensitive tracers of the sewage sludge to detect its presence. Identification of tracers early in the study increased the ability of investigators to recognize the sewage sludge signature and thereby to quantify sludge transport through the water and its fate in sediments. However, earlier and more frequent measurement of these and other tracers at actual levels in the sewage sludge might have enabled more refined

estimates of the amount of sludge reaching the seafloor and improved the ability to validate model results (Hunt *et al.*, 1995c).

The studies conducted under the 106-Mile Site monitoring and research program determined that a substantial fraction of the sewage sludge (minimally 20 to 30 percent, maximally 70 percent) reached the seafloor in and near the 106-Mile Site. Model calculations estimated that the remainder of the sludge, which settled through the ocean at slow rates, was transported in extremely diluted concentrations into the north Atlantic Ocean by the Gulf Stream. Both physical oceanographic measurements and model predictions indicated that sewage sludge dumped at the 106-Mile Site was not transported onto the continental shelf, nor to areas supporting commercial fisheries, nor to the shoreline of the eastern United States seaboard. Chemical and biological data collected on the continental shelf and submarine canyons, areas which support important commercial fisheries, corroborated this finding. Contaminant signatures in the canyons and on the outer continental shelf were more likely derived from transport of contaminant laden particles from the inner New York Bight, including down-canyon movement of sediments contaminated by historical disposal activities in the New York Bight, and atmospheric inputs.

Generally, the results developed under the transport and fate component of the study compare favorably with the predictions made during the site designation studies (Paul *et al.*, 1995). The monitoring and modeling demonstrated that vertical settling rates of the sludge in the water column were and remain problematic to the accuracy of the modeled fate (Paul *et al.*, 1995). Further, as is common to any scientific endeavor, the program identified additional data that would have enabled improved understanding of the fate and effects of the sludge dumping. Some of these include:

- i Earlier identification of chemical and physical characteristics of the sludge that could be used as tracers and for calibrating and validating predictive models.
- i Acquisition of sludge characteristics data at frequencies sufficient to reduce variability in loading calculations and improve mass balance estimates.
- i More complete characterization of size-specific, particle settling rates and associated chemical concentration of the sludge.
- i Consideration of ecological processes such as biological packaging and transport (Reed *et al.*, 1986) that might influence the transport and fate or effects (both positive and negative) of the material.

## CONCLUSIONS AND IMPORTANCE

Results from the 106-Mile Site program have added significantly to the understanding of many issues related to the transport, fate, and effects of sewage sludge disposal in deepwater environments. The information returned during the program provides a model for evaluating any future consideration of ocean disposal of similar wastes.

When all the studies of transport, fate, and effects are considered together, two conclusions emerge repeatedly. First, sewage sludge disposal at the 106-Mile Site, and the contaminants associated with that sludge, were rarely if ever transported to the outer continental shelf, and never to the inner shelf or seashore. Instead, the materials disposed at the 106-Mile Site were transported almost exclusively to the continental rise and slope and deposited there, or entrained in the Gulf Stream and carried out into the Atlantic Ocean. Hence, disposed sludge never came in direct contact with commercially important living marine resources and therefore was unlikely to have significant impact on those resources or human health.

The second generality that emanates from the 106-Mile Site studies is that no major direct adverse impact was identified on populations of non-commercial species which reside in or near the Site or along the continental slope down stream from the Site. Potential indirect effects from the bioaccumulation of contaminants in the sludge were also not identified because contaminant concentrations in the species studied were either low (consistent with historical information) or could not be related to the 106-Mile Site dumping activities. Furthermore, some studies in the 106-Mile Site program also looked for possible impacts on organisms and populations on the outer continental shelf (where sludge contaminants disposed at the 106-Mile Site would rarely penetrate, as demonstrated during the study). A prevailing theme in these latter studies was that seaward transport of the contaminants previously dumped inshore (*e.g.*, at the former 12-Mile Site in the inner New York Bight) was the likely source of the contaminants measured in the sediments and organisms on the outer continental shelf. Even though several possible impacts were identified, the effects were short lived or could not be separated from other activities (*e.g.*, fishing pressure).

It must be noted that the biological findings were based on an exposure period of only six years. Thus, extrapolation of the results to longer periods of disposal, greater volumes of sewage sludge, or other wastes must be done with caution. A more precise extrapolation to these scenarios awaits better knowledge of the routes of bioaccumulation and toxicological effects and a fuller understanding of whether changes that may occur are ecologically meaningful or unacceptable. Meanwhile, the biological findings from the 106-Mile Site program are encouraging in that

disposal of over forty-two million tons of sewage sludge in the ocean did not result in apparent negative impacts to ocean resources or threats to human health.

### **Acknowledgement**

Numerous people contributed in innumerable ways to the success of the 106-Mile Site Monitoring Program. Prior to 1989, 106-Mile Site monitoring studies were conducted under the guidance of Mr. Frank Csulak, formerly of EPA Region II and now with NOAA. Messieurs Richard Caspe and Bruce Kesilica of EPA Region II provided the senior oversight and made many difficult decisions regarding the permits and regulatory actions related to site management. Throughout the program Mr. Craig Vogt and Mr. John Lishman of the EPA Oceans and Coastal Protection Division provided EPA Headquarters oversight and guidance. We wish to thank them for their energetic involvement and commitment to the program. Appreciation is also extended to the hundreds of scientists, researchers, technicians, students and other support staff who conducted the day to day activities with enthusiasm and commitment to quality and to the captains and crews of the research vessels, without whom the program would not have succeeded.

This paper was initially prepared at Battelle Ocean Sciences under contract to the United States Environmental Protection Agency (Contract 68-C8-0134) and has been reviewed and approved for publication by the U.S.EPA and NOAA. The contents do not necessarily reflect the official views and policies of the U.S. EPA or NOAA.

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